International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1991 - Second International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

10 Mar 1991, 1:00 pm - 3:00 pm

Panel Reports: Discussions

Multiple Authors

Discussion of paper titled: "Liquefaction of Soils in the 1989 Loma Prieta Earthquake", by: Raymond B. Seed, Michael F. Riemer, and Stephen E. Dickenson, Paper No. LP02, by Marshall Lew, LeRoy Crandall and Associates

This paper presents a brief overview of the soil liquefaction occurrences documented during the 1989 Loma Prieta Earthquake in the Santa Cruz-San Francisco region of California. The paper first documents the liquefaction-related phenomena in the Marina District of San Francisco, and provides the historical backdrop in the development of the hydraulically filled area that experienced extensive liquefaction as evidenced by numerous sand boils and wide-spread lateral spreading. These phenomena resulted in damage to street pavements and buried utilities for water supply, sewer, and natural gas. Soil liquefaction also caused damage to structures by differential settlement, lateral spreading, and partial bearing failure. However, the authors attribute a majority of the structural damage to amplified strong ground shaking because the hydraulic fill soils are underlain by soft and compressible recent clayey estuarine deposits.

The paper also describes significant liquefaction in other parts of the affected region that have been less publicized. The paper describes the conditions in the Embarcadero and Old Mission Bay regions of San Francisco, which were previously damaged extensively in the 1906 San Francisco Earthquake. Soil liquefaction again occurred in these same areas and it is reported that one 15-block area had 50% of its structures significantly damaged or condemned. Considerable damage due to liquefaction was also found in the central eastern San Francisco Bay area. Extensive damage due to liquefaction occurred at hydraulically filled sites such as Treasure Island, Alameda Naval Air Station, Oakland International Airport, East Bayshore Freeway (Interstate 80) approach fill (mole) to the Bay Bridge, and the Port of Oakland. Of particular interest is the observation that battered piles used to support wharves at the Port of Oakland sustained substantial damage whereas wharves supported on only vertical piles fared better. Damage due to liquefaction along the Pacific coast between Half Moon Bay and Santa Cruz is also described. Closer to the fault rupture, widespread liquefaction occurred in alluvial channel deposits and caused damage to buildings, levees, and roads.

The authors state that the observations of liquefaction in this earthquake are in good conformance with currently used SPT-based liquefaction resistance correlations. The authors are troubled by the high levels of exposure of the public in San Francisco and Treasure Island and by the continued threat to critical facilities such as airport and harbor facilities. The vulnerability of lifeline utilities continues to highlight the earthquake fire hazard of the region. As the Loma Prieta Earthquake was only a moderate earthquake that was relatively distant from San Francisco, it serves as a precursor of worse events to come with closer and stronger events. Although they may be costly and politically unpopular, engineers need to educate the public and politicians to take steps to mitigate these hazards. More effort is also needed to improve our ability to mitigate the seismic exposures of existing structures and facilities.

Discussion of paper titled: "Lifeline and Geotechnical Aspects of the 1989 Loma Prieta Earthquake", by T.D. O'Rourke, H.E. Stewart, T.E. Gowdy, and J.W. Pease, Paper No. LP04, by Marshall Lew, LeRoy Crandall and Associates

The authors present an excellent overview of two aspects of the Loma Prieta Earthquake on areas in the City of San Francisco. Parallels are drawn with the phenomena and damages observed in the earlier 1906 earthquake. The authors report on the areas of San Francisco that have had historical evidence of soil liquefaction and large ground deformations in 1906; these same areas were investigated after the 1989 earthquake by the authors and they found that similar earthquake effects were again experienced.

The paper presents an examination of the two water supply systems in San Francisco; the first being the Municipal Water Supply System (MWSS) and the second being the Auxiliary Water Supply System (AWSS). The MWSS serves to provide potable water for domestic and commercial uses, including fire fighting. The AWSS was constructed after 1906 for emergency fire protection. The authors show that pipeline breaks were clustered in similar locations in liquefaction-prone areas in both the 1906 and 1989 events. A correlation was found between pipeline repairs per lineal length and the Modified Mercalli Intensity of shaking.

A study of the performance of AWSS system points out the need for an independent power supply for isolation valves at strategic locations to prevent large losses of water which would severely impact the ability of the fire department to battle fires. Computer simulations show the importance of fire hydrant breaks and how they could quickly drain the water reserves. The authors also report on the use of the fireboat "Phoenix" to help in fire fighting in the Marina District.

The paper also presents a concise detailed history of the development of San Francisco's Marina District and the geologic and soil conditions that exist there. The authors present the history of man-made fills and report on the placement methods used. The liquefaction potential of the hydraulic fill, land-tipped fill, and natural beach/sand bar deposits are evaluated. The understanding of the behavior of the different soil deposits in the Marina District provides an excellent opportunity to study lifeline vulnerability.

Discussion of paper titled: "Performance of Earth Dams During the Loma Prieta Earthquake", by Leslie F. Harder, Jr., Paper LP05, by Marshall Lew, LeRoy Crandall and Associates

This paper describes the performance of some 111 earth dams within 50 miles of the fault rupture zone of the Loma Prieta Earthquake. The majority of these dams are described as being essentially homogeneous. The maximum height of these earth dams ranges from less than 10 feet to over 300 feet. The ages of these dams range from just a few years to over 100 years old. The paper reports that the estimated peak ground accelerations for these affected earth dams range from 0.05 to almost 0.60g.

The paper reports that the 21 pre-1906 dams did not experience significant damage in the 1989 event; this is not unexpected since these same dams performed well in 1906. The paper summarizes the performance of some 35 dams that typify the inventory of dams in the affected region. Additional details are presented for 13 dams that experienced some distress. In general, the damages were minor, however, as described in detail in the paper, one major dam, the Austrian Dam, and one minor dam, Soda Lake Dam, had moderate damage. Minor to moderate cracking in a small number of other dams required repair.

The paper also reports on the strong ground motions recorded at 8 embankment dams. A comparison of peak transverse accelerations measured at both the base and crest of several earth and rockfill dams indicate that at low accelerations, there is relatively large amplification through the embankment dam. As the base accelerations become larger, the amount of amplification is reported by the author as being relatively low. One interesting observation in the paper concerns the well instrumented San Justo Dam where one strong motion sensor is embedded in a borehole approximately 62 feet below the crest of the dam. The motions recorded from the Loma Prieta Earthquake suggest that most of the transverse amplification took place within the upper half of the dam.

The author notes that although the performance of earth dams was generally good in this earthquake, a major contributing factor was that most of the reservoirs were at less than half of their maximum heights. However, the data from this earthquake will be valuable in understanding the behavior of earthfill dams.

Discussion of paper titled: "Liquefaction of Soils in the 1989 Loma Prieta Earthquake", by: Raymond B. Seed, Michael F. Riemer, and Stephen E. Dickenson, Paper No. LP02, by Marshall Lew, LeRoy Crandall and Associates

This paper presents a brief overview of the soil liquefaction occurrences documented during the 1989 Loma Prieta Earthquake in the Santa Cruz-San Francisco region of California. The paper first documents the liquefaction-related phenomena in the Marina District of San Francisco, and provides the historical backdrop in the development of the hydraulically filled area that experienced extensive liquefaction as evidenced by numerous sand boils and wide-spread lateral spreading. These phenomena resulted in damage to street pavements and buried utilities for water supply, sewer, and natural gas. Soil liquefaction also caused damage to structures by differential settlement, lateral spreading, and partial bearing failure. However, the authors attribute a majority of the structural damage to amplified strong ground shaking because the hydraulic fill soils are underlain by soft and compressible recent clayey estuarine deposits.

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The authors present an excellent overview of two aspects of the Loma Prieta Earthquake on areas in the City of San Francisco. Parallels are drawn with the phenomena and damages observed in the earlier 1906 earthquake. The authors report on the areas of San Francisco that have had historical evidence of soil liquefaction and large ground deformations in 1906; these same areas were investigated after the 1989 earthquake by the authors and they found that similar earthquake effects were again experienced.

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Discussion of paper titled: "Performance of Earth Dams During the Loma Prieta Earthquake", by Leslie F. Harder, Jr., Paper LP05, by Marshall Lew, LeRoy Crandall and Associates

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Discussion of paper titled: "Lifeline and Geotechnical Aspects of the 1989 Loma Prieta Earthquake", by T.D. O'Rourke, H.E. Stewart, T.E. Gowdy, and J.W. Pease, Paper No. LP04, by Marshall Lew, LeRoy Crandall and Associates

The authors present an excellent overview of two aspects of the Loma Prieta Earthquake on areas in the City of San Francisco. Parallels are drawn with the phenomena and damages observed in the earlier 1906 earthquake. The authors report on the areas of San Francisco that have had historical evidence of soil liquefaction and large ground deformations in 1906; these same areas were investigated after the 1989 earthquake by the authors and they found that similar earthquake effects were again experienced.

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DISCUSSION ON
"PERFORMANCE OF EARTH DAMS DURING THE LOMA PRIETA EARTHQUAKE"
BY
LESLIE F HARDER, JR.
(PAPER NO. LP05)
BY TATSUO OHMACHI, PROFESSOR
TOKYO INSTITUTE OF TECHNOLOGY, JAPAN

The above paper describes not only an overview but also detailed features of earthquake damage to earth dams in the San Francisco Bay Area. Typical damage described in the paper includes cracks on either crest or abutment, settlement, and liquefaction of tailings. With this information alone, the paper does not fail to give us invaluable lessons on earthquake resistance of dams. Nevertheless, it would be much more appreciated if the author could give us additional information; that is, information on seiching.

In the 1984 Morgan Hill earthquake, the seiching action was observed by a hydrogauge sensor which was located on the upstream face of the Anderson Dam. The recorded reservoir elevation data indicated that a disturbance with a peak-to-peak amplitude of 0.4 feet and period of about three minutes after the earthquake (Tepel et al, 1984).

According to the author, the reservoirs in many of the dams were quite low at the time of the Loma Prieta earthquake. Thus, supposedly, the seiching action did not have a signifficant effect on stability of dams in this case, but it might be induced to an extent larger than that observed in the Morgan Hill earthquake, because natural frequencies of the reservoirs with lower water level could be closer to predominant frequencies of the earthquake ground motion.

When the writer visited the Ambuklao Dam about one month after the 1990 Philippine earthquake, he was surprised to hear an eyewitness report on the seiching. According to the report,

> "..... big waves occured, about 5 meters in height, and such waves were found all over the reservoir area and lasted for about 30 minutes. ......"

Besides several longitudinal cracks on crest, a large settlement amounting to 80cm was observed on the downstream rockfill surface of the dam, as shown in Photo 1. To the writer's thinking, the seiching was liable to this settlement, at least in part.

Photo 1 Settlement of the Ambuklao Dam due to the 1990 Philippine earthquake

REFERENCE:

Tepel, R.E., Volpe, R.L. and Bureau, G.: Performance of Anderson and Coyote Dams During the Morgan Hill earthquake of 24 1984, CDMG Special Publication 68, 1984.

Discussion of paper titled: "Performance of a Pile-Supported Structure under Strong Ground Motion", by: Phillip L. Gould and Kijun Ahn, Paper No. LP07, by Marshall Lew, LeRoy Crandall and Associates

This paper examines the influence of soil-pile-structure interaction on the response of a mid-rise reinforced concrete hotel building located near San Francisco International Airport to the Loma Prieta Earthquake. Based on good correlations with a frame-shear wall model, a simplified stick model was used for most of the analyses. The pile-supported structure was modeled using a beam-column element with the mass at each floor level added to the nodal points as a lumped mass; rotational springs were attached to the nodal points to represent the bending moment resistance of the floor slabs. The pile foundations were modeled with nonlinear soil springs and dashpots and a rotational spring was attached at the base node to represent the rotational resistance due to the foundation slab and piles.

The model was subjected to the ground motions recorded at the nearby San Francisco International Airport. The paper reports that the influence of the soil-pile-structure interaction was significant on the response of the structure. The natural period increased 1.2 to 3.8 times the period of the fixed base structure as the rotational constraint at the base was decreased. As a result, the base shear and overturning moment were significantly reduced while the roof displacement increased. The authors believe that there is a potential for designing interactive pile foundation systems to function like base isolators.

There are two typographical errors in the text of the paper at the top of Page 1638 where the vectors of nodal point velocities and accelerations in iteration k should be denoted as $\{\dot{U}_i\}^{(k)}$ and $\{\ddot{U}_i\}^{(k)}$.

Discussion of paper titled: "Sanitary Landfill Performance During the Loma Prieta Earthquake", by: Dennis Buranek and Sangeeta Prasad, Paper No. LP14, by Marshall Lew, LeRoy Crandall and Associates

This paper compares the observed performance of six sanitary landfills in the affected area of the Loma Prieta Earthquake with the simplified method of estimating permanent deformation developed by Makdisi and Seed (1977). This method, based upon work first developed by Newmark (1965), assumes that permanent deformation will occur when a slope undergoes an acceleration exceeding a "yield acceleration".

The paper describes the observed damage or lack of damage at six sanitary landfill locations within 27 km of the projected fault rupture surface. Three of the sites were considered as rock sites, two of the sites were considered as alluvium sites, and one site was classified as being a soft soil site. Estimates of the mean peak horizontal accelerations at each site were made using strong-ground motion data from the USGS and CSMIP. These were compared with the calculated peak horizontal accelerations from several widely used attenuation relationships. For sites greater than about 20 km from the epicenter, the attenuation relationships were in reasonable agreement with the recorded data; at closer distances, however, the attenuation relationships predicted lower values than the actual recorded data.

Using published shear strength parameters for refuse, the authors analyzed the deformation of each of the landfill slopes by the technique of Makdisi and Seed. The predicted deformations were compared with the observed deformations (if any). The authors conclude that the Makdisi and Seed procedures appear to be an appropriate tool for evaluating the seismic performance of sanitary landfill slopes. The authors also note that considerable judgment is need for this type of analysis because of a lack of understanding in the static and dynamic behavior of sanitary landfill materials.

Discussion of paper titled: "Liquefaction and Surface Settlement in the Marina District", by D. Rosidi and W.B. Wigginton, Paper No. LP19, by Marshall Lew, LeRoy Crandall and Associates

The paper presents the results of a study of liquefaction potential of sands within the Marina District of San Francisco. Three types of potentially liquefiable soils are studied: (A) hydraulic fill, (B) artificial fill, and (C) Strawberry Island and other modern beach deposits. Dune sand deposits, although present in the Marina District, are excluded from this study because they have been shown to have little potential for liquefaction. The authors present representative profiles of each of the three soil types along with mean grain size and typical Standard Penetration Test (SPT) blow counts. The authors evaluated the potential for liquefaction of these soil profiles by the Liquefaction Resistance Factor method proposed by Iwasaki, et al. The studies indicated that a peak ground acceleration (PGA) between 0.05 and 0.1g is needed to initiate liquefaction and a PGA of about 0.1g is needed to produce any observable damage at the ground surface. The studies also predict that the entire thickness of saturated sand can liquefy under a PGA of 0.20g, 0.23g, and 0.30g for the hydraulic fill, Strawberry Island, and artificial fill, respectively. The authors speculate that the relatively short duration of the Loma Prieta earthquake may explain why the full thickness of the hydraulic fill did not liquefy. The authors also present computed settlements due to liquefaction for each of the three soil profiles in the Marina District and compare them with the observed settlements. The authors attribute the discrepancies between the computed and observed values are attributed to possible lateral spreading or other undefined factors.

Discussion of paper titled: "Performance of a Pile-Supported Structure under Strong Ground Motion", by: Phillip L. Gould and Kijun Ahn, Paper No. LP07, by Marshall Lew, LeRoy Crandall and Associates

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This paper examines the influence of soil-pile-structure interaction on the response of a mid-rise reinforced concrete hotel building located near San Francisco International Airport to the Loma Prieta Earthquake. Based on good correlations with a frame-shear wall model, a simplified stick model was used for most of the analyses. The pile-supported structure was modeled using a beam-column element with the mass at each floor level added to the nodal points as a lumped mass; rotational springs were attached to the nodal points to represent the bending moment resistance of the floor slabs. The pile foundations were modeled with nonlinear soil springs and dashpots and a rotational spring was attached at the base node to represent the rotational resistance due to the foundation slab and piles.

The model was subjected to the ground motions recorded at the nearby San Francisco International Airport. The paper reports that the influence of the soil-pile-structure interaction was significant on the response of the structure. The natural period increased 1.2 to 3.8 times the period of the fixed base structure as the rotational constraint at the base was decreased. As a result, the base shear and overturning moment were significantly reduced while the roof displacement increased. The authors believe that there is a potential for designing interactive pile foundation systems to function like base isolators.

There are two typographical errors in the text of the paper at the top of Page 1638 where the vectors of nodal point velocities and accelerations in iteration k should be denoted as $\{\dot{U}_i\}^{(k)}$ and $\{\ddot{U}_i\}^{(k)}$.

Discussion of paper titled: "Sanitary Landfill Performance During the Loma Prieta Earthquake", by: Dennis Buranek and Sangeeta Prasad, Paper No. LP14, by Marshall Lew, LeRoy Crandall and Associates

This paper compares the observed performance of six sanitary landfills in the affected area of the Loma Prieta Earthquake with the simplified method of estimating permanent deformation developed by Makdisi and Seed (1977). This method, based upon work first developed by Newmark (1965), assumes that permanent deformation will occur when a slope undergoes an acceleration exceeding a "yield acceleration".

The paper describes the observed damage or lack of damage at six sanitary landfill locations within 27 km of the projected fault rupture surface. Three of the sites were considered as rock sites, two of the sites were considered as alluvium sites, and one site was classified as being a soft soil site. Estimates of the mean peak horizontal accelerations at each site were made using strong-ground motion data from the USGS and CSMIP. These were compared with the calculated peak horizontal accelerations from several widely used attenuation relationships. For sites greater than about 20 km from the epicenter, the attenuation relationships were in reasonable agreement with the recorded data; at closer distances, however, the attenuation relationships predicted lower values than the actual recorded data.

Using published shear strength parameters for refuse, the authors analyzed the deformation of each of the landfill slopes by the technique of Makdisi and Seed. The predicted deformations were compared with the observed deformations (if any). The authors conclude that the Makdisi and Seed procedures appear to be an appropriate tool for evaluating the seismic performance of sanitary landfill slopes. The authors also note that considerable judgment is need for this type of analysis because of a lack of understanding in the static and dynamic behavior of sanitary landfill materials.

Discussion of paper titled: "Liquefaction and Surface Settlement in the Marina District", by D. Rosidi and W.B. Wigginton, Paper No. LP19, by Marshall Lew, LeRoy Crandall and Associates

The paper presents the results of a study of liquefaction potential of sands within the Marina District of San Francisco. Three types of potentially liquefiable soils are studied: (A) hydraulic fill, (B) artificial fill, and (C) Strawberry Island and other modern beach deposits. Dune sand deposits, although present in the Marina District, are excluded from this study because they have been shown to have little potential for liquefaction. The authors present representative profiles of each of the three soil types along with mean grain size and typical Standard Penetration Test (SPT) blow counts. The authors evaluated the potential for liquefaction of these soil profiles by the Liquefaction Resistance Factor method proposed by Iwasaki, et al. The studies indicated that a peak ground acceleration (PGA) between 0.05 and 0.1g is needed to initiate liquefaction and a PGA of about 0.1g is needed to produce any observable damage at the ground surface. The studies also predict that the entire thickness of saturated sand can liquefy under a PGA of 0.20g, 0.23g, and 0.30g for the hydraulic fill, Strawberry Island, and artificial fill, respectively. The authors speculate that the relatively short duration of the Loma Prieta earthquake may explain why the full thickness of the hydraulic fill did not liquefy. The authors also present computed settlements due to liquefaction for each of the three soil profiles in the Marina District and compare them with the observed settlements. The authors attribute the discrepancies between the computed and observed values are attributed to possible lateral spreading or other undefined factors.

A Written Discussion on the Engineering Aspects of the 1989 Loma Prieta Earthquake

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SYNOPSIS: The hazardous performance of Loma Prieta earthquake provides an opportunity to discuss the seismic damage especially in the San Francisco Bay region. And, numerous researches on the site amplification phenomena in the region have been released.
In this paper, some of the results concerning with the ground amplification effects in the soft alluvium are briefly introduced.

The distribution of the disastrous damage suffered from the 1989 Loma Prieta earthquake is condensed around the San Francisco Bay, the surface layer of which is composed of the soft soil such as the unconsolidated Bay Mud covered with the artificial landfill. The dynamic behavior of the soft landfill during the earthquake is reported by D. Buranek and S. Prasad in their paper of the number LP14 prepared for this conference, M.E. Johnson and his fellow workers in their paper of the number LP27 and H.D. Sharma and H.K. Goyal in their work of the number LP29, respectively. And, it is pointed out by H. Mizuno and his coworker A. Abe that the seismic intensity prediction based on the consideration of the local ground conditions may be necessary, which is recognized in Japan as the fundamental items to be incorporated into the building codes. According to the idea mentioned above, the distributions of the acceleration responses observed in the soft alluvium are made in comparison with those in the hard bedrock, and the damping effects in the soil grounds of different properties are evaluated, as shown in Fig. (A) after their manuscript of the number LP17.

On the other hand, for the purpose of obtaining the dynamic characteristics in the soil layer which is strongly affected with the earthquake, the experimental system in the composition of the handy apparatus is developed by K. Tokimatsu and his coworkers, which is capable to determine easily the spectral profile of the shearing wave velocities in a soil ground. It is expressed in their paper of the number LP13 that the method of the investigation is based on the behavior of the Rayleigh waves travelling dispersively along the ground surface, and that the results of the field test given in Marina District of San Francisco city are presented as the shearing wave velocities and the predominant periods distributed across the site, exhibited in Fig. (B) after their work.

Another field research has been carried out by T. Ohmachi and his coworkers who have made use of the microtremor, for the detection of the land amplification effects in the wide area of the San Francisco Bay region which includes Marina District on the north front of San Francisco city, the viaduct of Cypress street situated in Oakland city and collapsed heavily due to the earthquake, Embarcadero viaduct in the foot of Market District and the south of Market District standing on the old alluvium. The predominant spectra and the amplification factors obtained in the regions are adjusted on the base of their own concept about the ground amplified phenomena through microtremor measurements, as shown in Fig. (C) after their study of the number LP08. Following the materials in the work, it is designated that the distribution of the heavy damage suffered from the earthquake is much coincident with that of the large amplification factors over 5 when the predominant frequencies are around 1 Hz, which bears comparison with the result presented by K. Tokimatsu and et al. Under the field investigations about the geophysical properties mentioned ahead, the dynamic amplified behavior of the ground system having a soft alluvium is to be simulated in the San Francisco Bay region due to Loma Prieta earthquake.

As for the analytical procedures of examining the site amplified manner, the geological ground model with topographic irregularities subjected to seismic disturbances is prepared by E. Faccioli in his state of the art report of the number SOA7. Furthermore, the theoretical method of representing the seismic wave field composed of the slight sedimental basin standing alone on a half-basis under earthquake type loadings is prepared by K. Baba and his coworkers. In Fig. (D) after their work of the number LP06, the distributions of the response functions of the multiple laminated ground due to vertical excitations are shown along the surface, which are found clearly to concentrate on the portion of the soft deposit.

Finally, it is noted that the miserable experience through the earthquake is to be turned to a valuable lesson in advancing the aseismatic design of the structures constructed on the same type of the sedimental ground spread all over the seismic zone as the San Francisco Bay region.

REFERENCES

SOA7) Faccioli, E. (1991) Seismic amplification in the presence of geological and topographic irregularities.
LP06) Baba, K. and et al. (1991) On the site amplification characteristics in San Francisco Bay region due to the 1989 Loma Prieta earthquake type loadings.
LP08) Ohmachi, T. and et al. (1991) Ground motion characteristics of the San Francisco Bay area detected by microtremor measurements.
LP13) Tokimatsu, K. and et al. (1991) Considerations to damage patterns in the Marina District during the Loma Prieta earthquake based on Rayleigh wave investigation.
LP14) Buranek, D. and et al. (1991) Sanitary landfill performance during the Loma Prieta earthquake.
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LP27) Johnson, M.E. and et al. (1991) Investigation of sanitary landfill slope performance during strong ground motion from the Loma Prieta earthquake of October 17, 1989.
LP29) Sharma, H. and et al. (1991) Performance of a hazardous waste and sanitary landfill subjected to Loma Prieta earthquake.

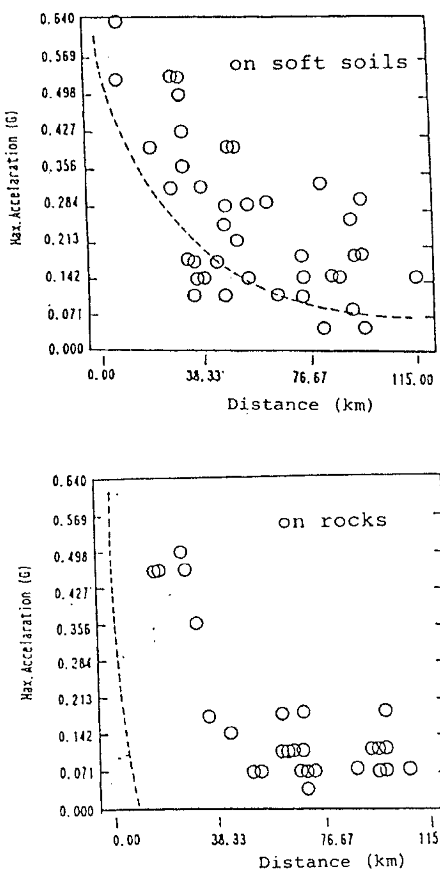

Fig. (A)
Max. accelerations and epicentral distances (after LP17)

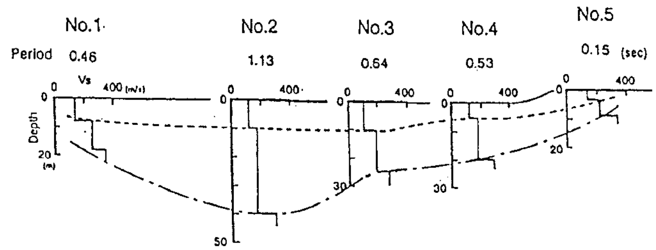

Fig. (B)
Cross section of shear wave velocity across the Marina District (after LP13)

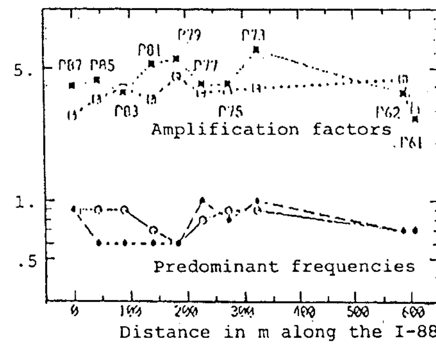

Fig. (C)
Predominant frequencies and amplification factors of the ground along Cypress Viaduct (after LP08)

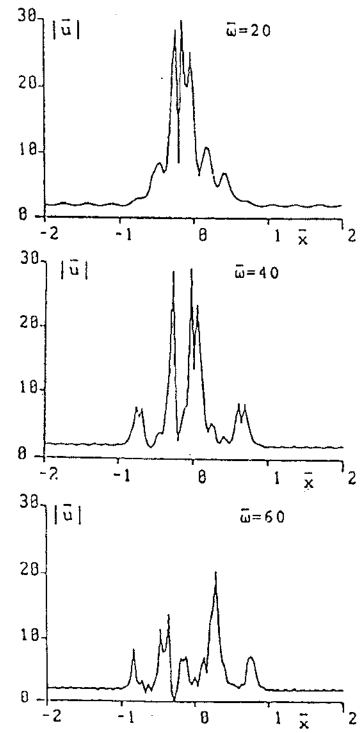

Fig. (D)
Amplification factors distributed on the multi-layered ground surface due to vertically incident waves (after LP06)